Effect of marine reserve establishment on non-cooperative fisheries management

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Abstract

Introducing effective marine reserves is a critical issue in fisheries management and marine ecosystem conservation. In recent years, a number of marine reserves or no-take marine protected areas (MPAs) have been implemented worldwide, and some MPAs have shown ecological and economic benefits. However, consideration for coordinated competition between institutions, a central for successful resource management, is often omitted in research on effective MPA management. Given increasing discussions on implementing MPAs in the high seas, where international fisheries often exemplify the tragedy of the commons, understanding potential competition between institutions can affect MPA management. With this in mind, we aimed to gain generic insight into non-cooperative fisheries management with MPAs. Specifically, we explored the effect of MPA establishment on (1) competition strength between fishery institutions, (2) fish population abundance resulting from the competition, and (3) distribution of the gross fishery profit between institutions. To approach these questions, we developed a minimal model that accounts a non-cooperative behavior of fishery institutions and population dynamics under the MPAs management. We demonstrate that, given a small price-to-cost ratio, a prominent increase in fishery competition could occur as a result of introducing an MPA, leading to reductions in fisheries profits and fish population abundance, and greater unevenness in distribution of the gross fishery profit. Intensified fishery competition was typically observed in the case where the rate of population exchange between the fishing grounds and the MPA is not large, and the fraction of the MPA is intermediate, suggesting that regulation agreements will be required to coordinate the competitive harvesting.

Keywords: fishery management, marine protected areas, non-cooperative resource management

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1. Introduction

The introduction of effective marine reserves has been a critical consideration in fisheries management and marine ecosystem conservation (Pikitch et al. 2004). Marine reserves or no-take marine protected areas (MPAs) are increasingly being used globally, both within national jurisdictions and in the high seas, and the pace of its new enforcement has been accelerated (Leenhardt et al. 2013; Edgar et al. 2014; Lubchenco and Grorud-Colvert 2015; Gill et al. 2017). This global trend has evoked a number of researches exploring the potential impact of MPAs establishment on marine ecosystems and a way to make MPAs management beneficial socially, economically, and ecologically (Baskett and Barnett 2015; Fulton et al. 2015, Gill et al. 2017).

Coordinating competition between institutions or fishers is of central importance for successful fishery management (Hardin 1968; Ostrom 1990; Pomeroy and Berkes 1997). Typically, fisheries that exploit highly migratory species that traverse multiple exclusive economic zones, and the high seas (~58% of the ocean) are more likely to overfish or deplete than those exploit exclusively (McWhinnie 2009) and these fisheries often exemplify the 'tragedy of the commons' (White and Costello 2014), a typical example of undesirable outcome of non-cooperative resource management. Also, illegal, unreported and unregulated (IUU) fishing has pervasively escalated in the past 20 years both within EEZ, and the high seas, and these lead to race to fish, overexploitations, and significant collateral damage to ecosystems (High Seas Task Force 2006; Ostrom 2008; Agnew et al. 2009). Given increased discussions concerning the high seas closure (Sumaila et al. 2007; Leenhardt et al. 2013; Lubchenco and Grorud-Colvert 2015), further insight into the potential impacts of MPA establishment on non-cooperative management, which is likely to occur in the high seas, or fisheries targeting a species that traverses multiple EEZs, would be of critically importance to predict management outcomes and give management implications to reduce the risk of producing a 'tragedy of the commons'. Although with prevalence of the tragedy of commons in fisheries management, previous researches of MPA management typically focus on the case of sole-owner management, where competition does not occur (e.g., Neubert 2003; Takashina et al. 2012; Kar and Ghosh 2013; Takashina and Mougi 2014; Ghosh et al. 2017). Limited research has been conducted on the strategic decision-making of fishers in the context of MPA management (Punt et al. 2010). Ruijs and Janmaat (2007) explored strategic MPA placement within a national boundary wherein two nations share the fishing resource through species migration. They found that 'the prisoner's dilemma' occurs in the absence of cooperation between countries. Sumaila (2002) simulated the economic rent over a 28-year-period of two non-cooperative management groups, using the specific example of the Northeast Atlantic cod fishery equipped with an age-structured two-patch model. With an assumption of one-directional fish migration from the MPA to the fishing grounds, the study concluded that economic rent is maximized when the size of the MPA is 50%–70% of the concerned region, and the standing biomass peaks around this point. Kellner et al. (2007) showed MPA establishment causes high fishing pressure along its boundary, resulting in fishers' competitive behavior to maximize catch per unit effort, and it equalizes the population abundance across the area outside the MPA.

Given deficiencies in previous studies, we aimed to gain generic insight into non-cooperative management with MPAs, and particularly (1) the effect of MPA establishment on strength of the competition behavior, (2) changes in population abundance as a result of the competition, and (3) distribution of the gross fishery profit between the fishery institutions. To address these issues, we developed a simple spatially-explicit model to account for non-cooperative behavior of fishery institutions and the population dynamics under the MPA management, and compare the management outcome with its sole-owner counterparts; the most common assumption of optimal fishing without competition. The model is a two-patch extension of the Schaefer model (Schaefer 1954): one patch represents the fishing grounds, wherein non-cooperative management takes place, and the other patch is an MPA, wherein no fishing activity occurs. We demonstrate that given a small price-to-cost ratio, a prominent increase in competition between institutions will occur owing to implementing the MPA, likely leading to well below fishery profit and population abundance than the sole-owner management, and greater unevenness in distribution of the gross fishery profit. Intensive competition would typically be observed when the population exchange rate between the fishing ground and the MPA is not large, and intermediate fractions of the MPA exist, suggesting that regulations will be required to coordinate competitive harvesting. Notably, it has repeatedly reported that, with these conditions, implementing MPAs can improve fishery profits as well as population abundance and reproductive capacity. However, our findings suggest that a careful implementation is needed under these conditions, since our results shows intensive competitions would occur in non-cooperative management, leading to well below benefit of MPAs management and population size compared to sole-owner management.

2. Methods

2.1 Non-spatial model for non-cooperative fisheries management

Here, we describe a model of non-cooperative fisheries management (hereafter, non-cooperative management) that accounts for the population dynamics of a target species and the spatial structure of the region concerned. We extend the Schaefer model (Schaefer 1954), which has been widely used in investigations of game-theoretic approaches to fisheries management (e.g., Mesterton-Gibbons 1993; Kaitala and Lindroos 2007), to a two-patch model so as to quantify the spatial effect on non-cooperative management (Fig. 1). The similar, spatially generalized Schaefer model was investigated in Takashina and Mougi (2015). Given a species' maximum growth rate per unit time *r*, carrying capacity *K*, catchability q_i, and the fishing effort of institution *i* per unit time e_i, the dynamics of population abundance *x* in the Schaefer model with *n*-institution fisheries is described as follows:

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right) - \sum_i^n q_i e_i x. \tag{1}$$

Following Clark (1990), given the price per unit of abundance harvested p_i and the cost per unit fishing effort of institution i, c_i, the equilibrium fisheries profit of institution i is

$$\pi_i = (p_i q_i x^* - c_i)e_i, \tag{2}$$

where, x^* is the equilibrium population abundance. To quantify the efficiency of fishery institution i, Mesterton-Gibbons (1993) defined the efficiency parameter as $b_i := c_i/(Kp_iq_i)$. By setting the value of the efficiency parameter properly, we can discuss, for example, the effect of improving fishing technology, which may lower the cost per unit fishing effort.

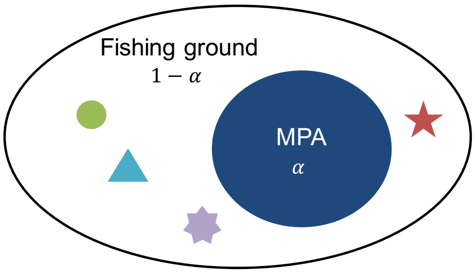

Figure 1: Schematic description of non-cooperative fisheries management with MPA establishment. Each symbol in the fishing grounds represents a different institution, whereby each institution makes a rational decision in terms of maximizing its own fisheries profit; $1-\alpha$ and α, respectively, are the fractions of the fishing grounds and the MPA.

2.2 Model with two-patch extension for non-cooperative management

A spatially explicit model of non-cooperative management is highly complex, and hence is not feasible for deriving analytical results except in certain extreme situations, such as where a species has an extremely high migration rate m. To make the discussion clearer here, we restricted ourselves to the simplest possible situation. Namely, we considered a two-institution two-patch extension of the Schaefer model, where one patch represents open fishing grounds and the other patch represents an MPA (Fig. 1), and the two patches are connected by a simple manner of fish movement or migration. However, to check the sensitivity of our minimal assumptions, more complex situations, such as n-institution management under some extreme conditions or different migration schemes of the species, are considered in Appendix A and B.

As mentioned, in the model, migration of a target species connects the two patches. By adding an exchange term to Eq. (1), a two-patch extension of the Schaefer model may be described as

$$\frac{dx_1}{dt} = rx_1\left(1-\frac{x_1}{K_1}\right) - \sum_i^2 q_i e_i x_1 + M(x_1, x_2), \tag{3a}$$

$$\frac{dx_2}{dt} = rx_2\left(1-\frac{x_2}{K_2}\right) - M(x_1, x_2), \tag{3b}$$

where, x_j is population abundance in patch j, and where j = 1 and 2 are the fishing grounds and the MPA, respectively. $K_1 = (1-\alpha)K$ and $K_2 = \alpha K$ are the carrying capacity of patch 1 and 2, and $1-\alpha$ and α are the areal fractions of the fishing grounds and the MPA, respectively. Finally, $M(x_1, x_2)$ is the population-exchange function between the two patches. One of the simplest forms of the migration term may be $M(x_1, x_2) = m(a_{21}x_2 - a_{12}x_1)$, where m is the population exchange rate between patches, with the patch-specific weighting term $a_{jj'}$ denoting migration from patch j to j'. Letting $a_{jj'}$ be proportional to the areal fraction of the destination patch, we obtain a random migration form (Takashina and Mougi 2015):

$$M(x_1, x_2) = m\{(1-\alpha)x_2 - \alpha x_1\}, \tag{4}$$

where, the population exchange rate m now has the dimensions of time and area. Because only the population in the fishing grounds contributes to the fisheries profits, then x^* in Eq. (2) is replaced with x_1^* for the fishery profit of institution i in the spatially explicit harvest model.

Under non-cooperative management, each institution makes a rational decision, under which no change in their allowable choices increases their profits. This solution is the so-called Nash equilibrium (Nash 1951). The objective function of non-cooperative management is shown as:

$$\pi_i^{\mathrm{Nash}_2} = \max_{e_i}\left(p_i q_i x_1^{\mathrm{Nash}_2} - c_i\right)e_i, \qquad (i = 1, 2) \qquad (5)$$

where, the superscript Nash_2 indicates the Nash equilibrium under a situation of two-institution management. To investigate the spatial effect of non-cooperative management, we also calculated the optimal profit under sole-owner management. Specifically, if management is conducted by a sole owner, we write Eq. (5) as $\pi^{\mathrm{Sole}} = \max_{e_s}\left(p_s q_s x_1^{\mathrm{Sole}} - c_s\right)e_s$ where the subscript s indicates the sole-owner management counterparts of the parameters defined above. In addition, we assume that the sole owner can chose one of the better management options: $b_s = \min(b_1, b_2)$; because π^{Sole} is clearly the Pareto-optimal, then $\sum_i^2 \pi_i^{\mathrm{Nash}_2} \leq \pi^{\mathrm{Sole}}$ is always satisfied.

2.3 Measures to quantify the spatial effect on non-cooperative management

Next, we introduced measures to quantify the spatial effect of non-cooperative management in relation to the result in the case of sole-owner management. For convenience, we use the letter ρ for all the measures defined below.

Changes in intensity of competition between the institutions may be measured through the fractional decline in gross fishery profit over the two institutions from the Pareto-optimal profit:

$$\rho^{\mathrm{fp}_2} = \frac{\pi_1^{\mathrm{Nash}} + \pi_2^{\mathrm{Nash}}}{\pi^{\mathrm{Sole}}}, \qquad (6)$$

where, the subscript 2 represents the number of actual institutions, and the same notation is used for the other measures. As π^{Sole} is the Pareto-optimal, $0 \leq \rho^{\mathrm{fp}_2} \leq 1$ is satisfied, and a smaller value indicates more intense competition; but if $\rho^{\mathrm{fp}_2} = 1$, then no competition occurs. Specifically, we define $\rho^{\mathrm{fp}_2} = (0+0)/0 = 0$, and this may occur when the fraction of the MPA is sufficiently large and then fishery is not anymore profitable.

For determining evenness of the distribution of the gross fishery profit between the two institutions, we define

$$\rho^{\mathrm{ev}_2} = \frac{\pi_1^{\mathrm{Nash}}}{\pi_1^{\mathrm{Nash}} + \pi_2^{\mathrm{Nash}}}, \qquad (7)$$

where, ρ^{ev_2} also satisfies the inequality $0 \leq \rho^{\mathrm{ev}_2} \leq 1$. Hence, $\rho^{\mathrm{ev}_2} = 0$, 1/2 or 1, respectively, are achieved when institution 1 does not make any profit ($\pi_1^{\mathrm{Nash}} = 0$), the gross profit obtained by the two institutions is equally distributed ($\pi_1^{\mathrm{Nash}} = \pi_2^{\mathrm{Nash}}$), or institution 1 takes the entire profit ($\pi_2^{\mathrm{Nash}} = 0$). An equal distribution of the fisheries profits arises if the two institutions have identical values in the efficiency parameter, that is $b_1 = b_2$.

Besides measures related to economic factors, we also defined an ecological measure quantifying the impact of harvesting competition on population abundance. Given that the total population abundance ($X = x_1 + x_2$) resulted in a non-cooperative strategy as did sole-owner management, represented as X^{Nash_2} and X^{Sole}, respectively, we define

$$\rho^{\mathrm{pa}_2} = \frac{X^{\mathrm{Nash}_2}}{X^{\mathrm{Sole}}}. \quad (8)$$

Intensive competition by way of intensive fishing effort may reduce this value.

2.4. Numerical simulation

In numerical study, without loss of generality, we set $q = q_i = 1$ (i =1, 2) and assumed that any changes in the efficiency parameter of institution i, b_i, would be reflected in change in the cost of fishing effort c_i. Hence, we set $p = p_i = 1$, and thus $pq = p_i q_i = 1$ (i =1, 2). We examined three orders of magnitude difference in the value of the cost of fishing effort c_i: one order of magnitude smaller, one order of magnitude larger, and the same magnitude in comparison with the value for price per unit of harvest p. Specifically, we examined the three orders of magnitude difference in values for the price-to-cost ratio p/c_i.

3. Results

Simulations under the situation where two institutions have a comparable efficiency parameter ($b_s = b_1 = b_2$) showed that the introduction of an MPA increases the intensity of competition between the institutions, resulting in smaller values of ρ^{fp_2} (Fig. 2, top). This effect is prominent when the cost of fishing effort c_i is small, and it is suppressed as the cost of fishing effort increases. Not surprisingly, if the cost of fishing effort is sufficiently high ($c_i = 10$ in this example) and the fraction of the MPA α becomes large, the fishery does not make a profit (Fig. 2, top right). More intense competition (i.e., when the value of ρ^{fp_2} is small) is typically observed when the fraction of the MPA is an intermediate value and the value of the exchange rate m is less than 10. As expected, the proportion of total population abundance ρ^{pa_2} tends to be smaller when the intensity of competition is higher (Fig. 2, bottom), suggesting that introduction of an MPA can result in reduced population abundance as compared with a situation of sole-owner management. However, if the rate of population exchange between the patches is small (i.e., m is near 0.1), this effect is suppressed.

Next, we considered the situation where one institution has a smaller value for the efficiency parameter than does the other institution ($b_s = b_1 < b_2$). Specifically, we set $b_s = b_1 = 0.8b_2$, and, by the assumption above, this is reflected in the cost of fishing effort, $c_s = c_1 = 0.8c_2$. Despite different values for the efficiency parameter, we still obtained qualitatively similar results for the fractional decline of the gross fishery profit (ρ^{fp_2}) and the proportion of total population abundance (ρ^{pa_2}) (see Fig. 3, top and middle). However, the distribution of the gross fishery profit between the two institutions became uneven, and was biased toward the institution with a lower value for the efficiency parameter (i.e., institution 1 tended to get a larger share of the profits in the parameter space investigated: $\rho^{\mathrm{ev}_2} \geq 1/2$). Notably, this bias was prominent when the intensity of competition was high (i.e., when the value of ρ^{fp_2} is small; Fig. 3, bottom). In this example, institution 1 had 20% smaller values for the efficiency parameter, yet qualitatively similar results were obtained when institution 1 was assigned 40% smaller values for the efficiency parameter, $c_s = c_1 = 0.6c_2$ (Appendix C, Fig. C3).

Along with the simulation results described above, we also examined the effect of n-player harvesting, different forms of population exchange between the patches, a density-dependent exchange rate (Appendix B, Figs. B1 and B2), and parameter sensitivity (Appendix C, Figs. C1–C3). Overall, we found that in several cases, harvesting competition became intense as a result of introducing an MPA, and this was typically observed in a parameter space where the population exchange rate is not high and the fraction of the MPA is intermediate (corresponding to the results presented in Figs. 2 and 3, top). In addition, such a case was likely to occur when the cost of the fishery effort is small, or the maximum growth rate/carrying capacity of the target species is large. In addition, we also gave an analytical form to the three measures of harvesting competition of two or n-player harvesting (Eqs. 6–8) wherein the population exchange rate had an extreme value ($m = 0$ or $m \gg 1$). In such situations, the degree of harvesting competition increased as the number of institutions increased, corresponding to results obtained in a non-spatially explicit harvest model by Mesterton-Gibbons (1993).

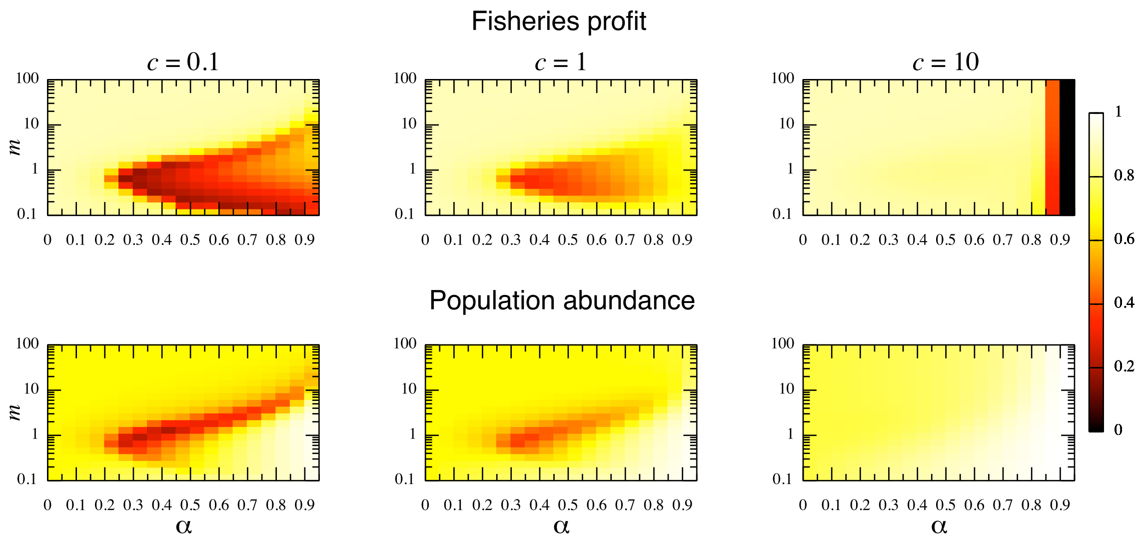

Figure 2: Non-cooperative fisheries management with MPA establishment. The x axis is the MPA fraction (i.e., the right-side patch shown in Fig. 1; $0 \leq \alpha \leq 0.95$), and the y axis is the population exchange rate between the patches, m. Each column shows different costs of fishing effort (c = 0.1, 1, 10). The first row of figures shows the fractional decline in gross fishery profit ρ^{fp_2} relative to a scenario of sole-owner management (see Eq. 6). The second row of figures shows that the proportion of total population abundance, $X^{\mathrm{Nash}_2}/X^{\mathrm{Sole}}$ (see Eq. 8), where the numerator and denominator are resulted in non-cooperative management and sole-owner management scenario, respectively. Other parameter values are r = 1, K = 100. Note that when the fraction of the MPA α is 0, it corresponds to the (non-spatially explicit) Schaefer model.

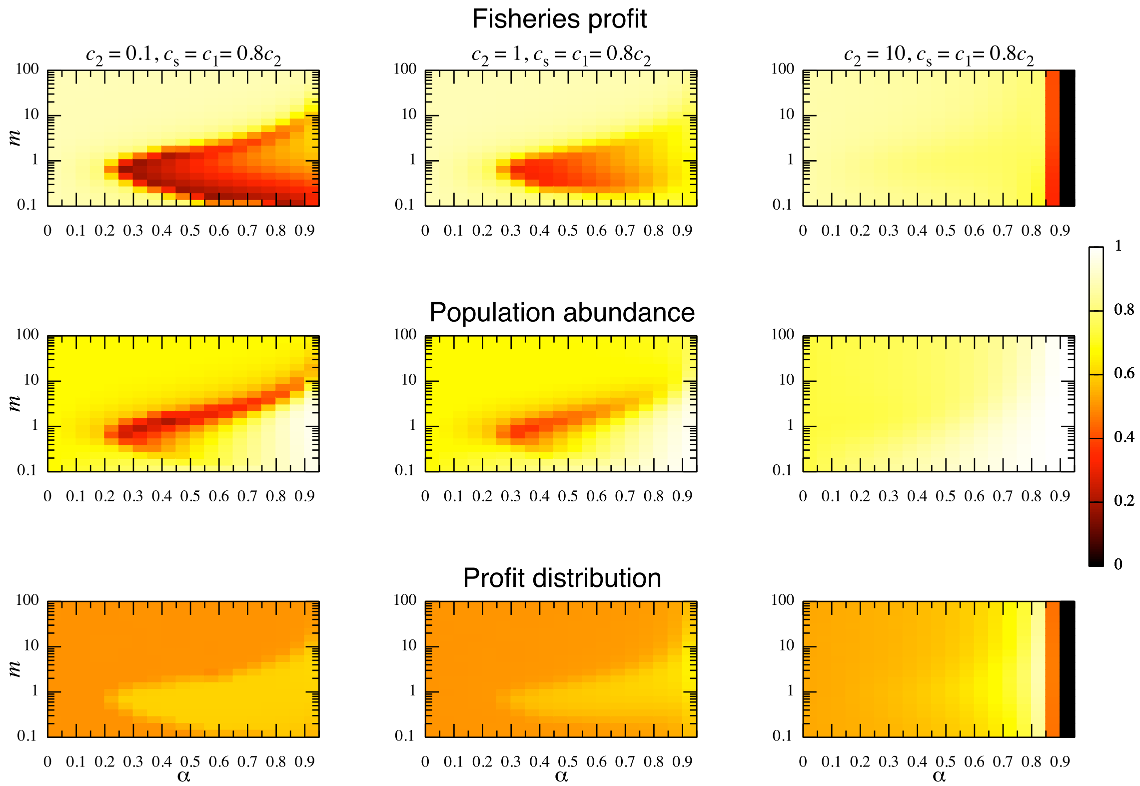

Figure 3: Non-cooperative fisheries management with MPA establishment but with different efficiency parameters ($b_s = b_1 = 0.8b_2$, equivalently $c_s = c_1 = 0.8c_2$). The x axis is the fraction of the MPA (i.e., the right-side patch shown in Fig. 1; $0 \leq \alpha \leq 0.95$), and the y axis is the population exchange rate between the patches m. Each column shows different costs of fishing effort ($c_2 = 0.1,\ 1,\ 10$; the notations of the first and second rows of figures are the same as for Figure 2). The third row of figures represents evenness in distribution of the gross fishery profit between the two institutions (see Eq. 7).

Discussion

By developing a simple spatially-explicit model of non-cooperative fisheries management in the context of MPA establishment, we investigated how introducing an MPA might change the degree of harvesting competition, the population abundance as a result of the competition, and the distribution of gross fishery profit between two institutions. With a small price-to-cost ratio we found that a prominent increase in harvesting competition could occur owing to introducing an MPA, leading to a largely lower fishery profit as well as reduced population abundance as compared with a scenario of sole-owner management. In addition, when the efficiency parameter values differed between the institutions, unevenness in distribution of the gross fishery profit increased as harvesting competition intensified. The simulations showed that intense competition is typically observed in a parameter space where the population exchange rate between the fishing grounds and the MPA is not large, and the fractions of the MPA is intermediate. Notably, in the context of sole-owner management within such a set of parameter values, it is well known that implementing MPAs can improve fisheries profits as well as population abundance and reproductive capacity (Gerber et al. 2003;

Moffitt et al. 2009; Williams et al. 2009; Goñi et al. 2010; Gruss et al. 2011). Importantly, the present findings suggest that consideration for the outcomes of non-cooperative management and ways to regulate especially intensive harvesting competition is crucial for implementing effective MPAs.

The inefficiency of fisheries management with MPA establishment by way of increased levels of harvesting competition is mainly caused by the generally open-access regime, exacerbating a ‘prisoner’s dilemma’ through the high capability of the fishing effort. Indeed, an increase in fishing effort is suppressed when the cost of the fishing effort is large enough, thereby suppressing the prisoner’s dilemma through the small capability of the fishing effort (Figs. 2 and 3, top right). Fisheries regulations that directly increase the cost of fishing effort may be possible. Rearranging a given amount of subsidies would provide a basis for potential regulation, since government subsidies enable fishers to exert a larger fishing effort (Munro and Sumaila 2002; Pauly et al. 2002). For example, a reduction in fuel subsidies may reduce the capability of fishing efforts (Sumaila et al. 2008) and this may in turn increase the value of the cost of fishing effort and suppress harvesting competition between institutions; as in the effect in Figs. 2 and 3, top right.

Instead of direct regulation of fishing capability, limited access or clarification of resource-use rights are alternative ways to achieve successful resource management (Ostrom 1990; Ostrom et al. 1992). Limited access adjusts harvesting by the stakeholders, motivating them to develop and implement harvesting rules. Fisheries co-management, which is widely applied in situations of small-scale or coastal management (Hilborn et al. 2005; Makino and Matsuda 2005; Matsuda et al. 2010), is one such example—demonstrated to improve participation in decision-making processes of multi-level governance and mitigate conflicts between institutions by developing management rules (Pomeroy and Berkes 1997; Jentoft et al. 1998; Hilborn et al. 2005). For many pelagic fishes instead, such as bluefin tuna, is managed under regional fisheries management organizations (RFMOs) comprising multi-member states (Boustany 2011). Members of RFMOs develop and agree upon the conservation framework and management measures for the target species, as well as on implementation at the country level (Boustany 2011).

As mentioned above, limited access and inclusive decision-making bodies are essential treatments to mitigate the so-called prisoner’s dilemma. However, the available literature shows that the prisoner’s dilemma could still easily occur when mutual trust between institutional members and/or harsh punishments for rule-breakers are lacking (Yamagishi 1986; Boyd and Richerson 1992; Fehr and Gächter 2000). Developing surveillance, monitoring network, and traceability of catch have been proposed to prevent illegal fishing (High Seas Task Force 2006; Agnew et al. 2009; Flothmann et al. 2010; Borit and Olsen 2012; Österblom 2014). Territorial-use rights in fisheries (TURFs) introduced to co-management situations is one way to facilitate fisheries surveillance (Hilborn et al. 2005). For instance, TURF systems are applied to nearshore coastal fisheries in Japan and Chile (Matsuda et al. 2010; Cancino et al. 2007), to assure that the different fishers have a degree of ownership of the resource in an allotted area.

Lack of fairness or satisfaction among all stakeholders for the established management policies may also lead to poor management outcomes. For example, suppose the efficiency parameter values are highly heterogeneous among institutions (e.g., different costs of fishing effort), yet the same harvesting quota is assigned to each institution regardless of their efficiency. With the homogeneous harvesting quota, an institution with sufficiently high efficiency may be tempted to break rule to seek even more profit by increasing the fishing effort. (McFadden 1976; McKelvey and Palfrey 1995). In such a situation, discussions aimed at balancing economic efficiency and fairness among the various institutions are fundamental for arriving at effective management rules. There are a body of researches motivated to understand the mechanism to overcome unintended outcomes of resource management through fields researches, laboratory experiments, and game theoretic studies (Ostrom 1990; Ostrom et al. 1994; Ostrom 2009; Tavoni et al. 2012; Iwasa and Lee 2013; Lee et al. 2015) Incorporating these approaches into our spatially-explicit management model may further develop our insight into MPAs management with non-cooperative situations.

In addition, ecological aspects are also important considerations to guarantee that developed management regimes work properly: animal migration may cause incomplete coordination of the property rights, also leading to the prisoner's dilemma. For example, in TURFs management, the size of each TURF should be carefully chosen based on ecological knowledge of a target species, particularly since TURFs encompassing smaller areas may cause incomplete property rights because of adult spillover and larval export, ultimately intensifying competition between the harvesters of each TURF (White and Costello 2011).

Along with management schemes, the movement and manner of species migration between patches are also known to affect the performance of an implemented MPA by changing the degree of adult spillover (Gruss et al. 2011; Takashina et al. 2012; Takashina and Mougi 2014). Although we examined the effect of density dependence in the population exchange scheme (Appendix C, Figs. C1 and C2) as part of an ecologically plausible manner of relocation, it is not an easy task to judge whether the density-dependent effect occurs, and there may be a time-lag for before the effect takes place if the stock size decreases before implementing an MPA (Gruss et al. 2011). Nevertheless, assessing the population exchange rate between adjacent patches plays a central role in effective implementation of MPAs.

Here, we showed that consideration for institutions' non-cooperative behavior in relation to MPA establishment is of critical importance when assessing the effectiveness of an MPA. Our results suggest that the implementation of an MPA must be accompanied by regulations to ease competition between institutions harvesting in the adjacent areas. To acquire basic insight into the non-cooperative behavior in relation to MPA management, we necessarily omitted some otherwise important ecological and economic aspects, such as age/size-structure in the population dynamics of the targeted species, multiple-species consideration, and non-infinitely elastic demand for the fish resource. Although consideration of these aspects in this study would have increased the difficulty of extracting general insight, they will unavoidably need to be applied to specific management situations.

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Appendix of Effect of marine reserve establishment on non-cooperative fisheries management

by

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Appendix A Analytical results at $m \gg 1$ and $m = 0$

Although even our simplest possible model for non-cooperative fisheries management with MPAs is not amenable a mathematical analysis, we can get some analytical results at some extreme conditions such as when the exchange rate has extreme values $m \gg 1$ and $m = 0$. Here, we describe some results under such extreme conditions. Note unlike the analysis in the main text, we do not restrict ourselves to the assumption of two-player management as well as an identical efficiency parameters.

Appendix A.1 Aggregated form of Eq. (1) with the sufficient large exchange rate $m \gg 1$

Here, we give an approximated form of Eq. (1). When the time scale of the exchange rate, m, is significantly smaller than other parameters ($m \gg 1$) the effect of the exchange between the patches on the entire population abundance ($X = x_1 + x_2$) is sufficiently small at the time scale of the population dynamics, τ. In such situation, the aggregation method [1–3] gives the approximated form of Eq. (3):

$$\frac{dX}{d\tau} = rX\left(1 - \frac{X}{K}\right) - (q'_1 e_1 + \cdots + q'_{n_a} e_{n_a})X, \tag{1}$$

where, $q'_i = (1-\alpha)q_i$ and n_a is the actual number of institutions. Note under the sole-owner management, in the parentheses of the second term becomes $q'_s e_s$, where q'_s and e_s are the catchability and the fishing effort of the sole-owner management, respectively. By the same assumption that sole-owner management is based on the fisheries parameters of one of the existing institutions as in the main text, $s \in \{1, \ldots, n_a\}$ is assumed. The fisheries profit of the institutions i is

$$\pi_i = \left(p_i q'_i X^* - c_i\right) e_i, \quad i \in \{1, \ldots, n_a\} \tag{2}$$

Using the result obtained by Mesterton-Gibbons [4], we easily deduce the rational choice of institution i in our spatially-explicit model

$$q'_i e_i = \begin{cases} \frac{r}{n_a+1}\left[1 - \frac{1}{1-\alpha}\left(n_a b_i - \sum_{j\neq i}^{n_a} b_j\right)\right], & \text{if } 1 \le i \le n_p \\ 0, & \text{if } i > n_p \end{cases} \tag{3}$$

where, n_a is the actual number of institutions, and

$$n_p = \max\left[k | k b_k < 1 - \alpha + \sum_{i}^{k-1} b_i\right], \tag{4}$$

is the potential number of users among which the economically feasible fishery is plausible, hence $n_a \le n_p$. $b_i := c_i/(K p_i q_i)$ is the efficiency parameter of institution i [4], and by the same assumption as in the main text, we set $b_s = \min\{b_1, b_2, \cdots, b_{n_a}\}$. We also assume that any institutions By Eq. (3), we can calculate the total fishing pressure:

$$\sum_{i}^{n_a} q'_i e_i = \frac{r n_a}{n_a + 1}\left(1 - \frac{\langle b\rangle_{n_a}}{1-\alpha}\right), \tag{5}$$

where, $\langle b\rangle_{n_a}$ is the average of the efficiency parameter over the n_a institutions, namely $\langle b\rangle_{n_a} := \sum_i^{n_a} b_i/n_a$. Specifically, we define $\langle b\rangle_1 := b_s$. By substituting Eq. (5) into Eq. (1), the Nash equilibrium population abundance under the n_a-player's non-cooperative management is

$$X_{n_a}^{\mathrm{Aggre}} = \frac{K}{n_a+1}\left(1+\frac{\sum_i^{n_a} b_i}{1-\alpha}\right). \tag{6}$$

Given Eqs. (3) and (6) we can calculate the profit by Eq. (2) given rational choice of institutions

$$\pi_i^{\mathrm{Aggre}} = \frac{p_i r K}{(n_a+1)^2}\left\{1-\frac{1}{1-\alpha}\left(n_a b_i - \sum_{j\neq i}^{n_a} b_j\right)\right\}^2. \tag{7}$$

Eq. (6) and (7) give values for the sole-owner management if $n_a = 1$, and for the non-cooperative management if $1 < n_a \leq n_p$. We can calculate the Eqs. (6) and (8) as a n_a-institution case:

$$\hat{\rho}^{\mathrm{fp}_{n_a}} = \frac{4}{(n_a+1)^2}\left(\frac{\sum_i^{n_a}\{1-\alpha-(n_a b_i - \sum_{j\neq i} b_j)\}^2}{(1-\alpha-b_s)^2}\right), \tag{8}$$

$$\hat{\rho}^{\mathrm{pa}_{n_a}} = \frac{2}{n_a+1}\left(\frac{1-\alpha+\sum_i^{n_a} b_i}{1-\alpha+b_s}\right), \tag{9}$$

where, $\hat{\rho}^{\cdot}$ represents the quantity obtained by the aggregation method. For $\hat{\rho}^{\mathrm{fp}_{n_a}}$ and $\hat{\rho}^{\mathrm{pa}_{n_a}}$, we obtain the following proposition.

Proposition A1 Eqs. (8) and (9) satisfy the following properties:
(P1) $d\hat{\rho}^{\mathrm{fp}_{n_a}}/d\alpha \leq 0$,
(P2) $d\hat{\rho}^{\mathrm{pa}_{n_a}}/d\alpha > 0$.

Since the statement P2 is obvious, we only show that the statement P1 holds. By differentiating Eq. (8) with α, we obtain

$$\frac{d\hat{\rho}^{\mathrm{fp}_{n_a}}}{d\alpha} = \frac{8}{(n_a+1)^2}\Bigg[(1-\alpha-b_s)\sum_i^{n_a}(1-\alpha-(n_a b_i - \sum_{j\neq i}^{n_a} b_j)) \tag{10}$$

$$\times \quad \{(1-\alpha-(n_a b_i - \sum_{j\neq i}^{n_a} b_j)) - (1-\alpha-b_s)\}\Bigg] / (1-\alpha-b_s)^4, \tag{11}$$

where, we find that we only require to show the sign of inside the bracket. Let $\theta_i := 1-\alpha-(n_a b_i - \sum_{j\neq i}^{n_a} b_j)$, $M = \max\{\theta_1, \theta_2, \cdots, \theta_{n_a}\}$, and $M' = (1-\alpha-b_s)M$. With the condition Eq. (4), we obtain

$$
\begin{aligned}
&(1-\alpha-b_s)\sum_i^{n_a}(1-\alpha-(n_a b_i-\sum_{j\neq i}^{n_a} b_j))\{(1-\alpha-(n_a b_i-\sum_{j\neq i}^{n_a} b_j))-(1-\alpha-b_s)\}\\
&\leq M'\sum_i^{n_a}\{(1-\alpha-(n_a b_i-\sum_{j\neq i}^{n_a} b_j))-(1-\alpha-b_s)\},\\
&= M'\sum_i^{n_a}(b_s-b_i),\\
&\leq 0,
\end{aligned} \tag{12}
$$

where, to get the last line, we used the assumption $b_s = \min\{b_1, b_2, \cdots, b_{n_a}\}$. Equality is achieved when $b_i = b_s$ holds for all i. Thus, the statement P1 holds.

The proposition suggests that, in relation to the sole-owner management, an increase of the MPAs fraction, α, decreases the gross fisheries profit of the non-cooperative management, and increases the population abundance.

Example: two-player management

As in the main text, here we give some results of the aggregated model of two-player's non-cooperative management. Substituting $n_a = 2$ into Eqs. (8) and (9), we obtain

$$\hat{\rho}^{\mathrm{fp}_2} = \frac{4}{9}\left(\frac{\sum_i\{1-\alpha-(2b_i-b_{j\neq i})\}^2}{(1-\alpha-b_s)^2}\right), \qquad (i,j=1,2) \tag{13}$$

$$\hat{\rho}^{\mathrm{pa}_2} = \frac{2}{3}\left(\frac{1-\alpha+b_1+b_2}{1-\alpha+b_s}\right). \tag{14}$$

Specifically, when $b \coloneqq b_s = b_1 = b_2$, we obtain

$$\hat{\rho}^{\mathrm{fp}_2} = \frac{8}{9}, \tag{15}$$

$$\hat{\rho}^{\mathrm{pa}_2} = \frac{2}{3}\left(\frac{1-\alpha+2b}{1-\alpha+b}\right). \tag{16}$$

We verify that the values shows in Fig. 2 in the main text approaches these values as the exchange rate, m, becomes large. Because of the Proposition A1., an increase of the MPA fraction increases ρ^{pa_2}. Eq. (15) does not contain the MPA fraction α, and this situation is equivalent to the result obtained by non-spatial model Eq. (1) in the main text.

In the two-player's non-cooperative management, we can also obtain evenness of the distribution of the gross fisheries profit defined in the main text (Eq. 7):

$$\hat{\rho}^{\mathrm{ev}_2} = \frac{\{1-\alpha-(2b_1-b_2)\}^2}{\sum_i\{1-\alpha-(2b_i-b_{j\neq i})\}^2}. \qquad (i,j=1,2) \tag{17}$$

As in the main text, we set $b_1 \leq b_2$. Then we get $d\hat{\rho}^{\mathrm{ev}_2}/d\alpha > 0$, and clearly $\hat{\rho}^{\mathrm{ev}_2} \geq 1/2$, suggesting that an increase of the MPAs fraction increases unevenness of the profit distribution.

Appendix A.2 Solution when no exchange occurs $m = 0$

We consider the situation where no exchange of the populations between the fishing ground and MPAs occurs ($M(x_1, x_2) = 0$). In this situation, the model is simplified as

$$\frac{dx_1}{dt} = rx_1\left(1 - \frac{x_1}{K_1}\right) - \sum_i^{n_a} q_i e_i, \tag{18}$$

$$\frac{dx_2}{dt} = rx_2\left(1 - \frac{x_2}{K_2}\right), \tag{19}$$

By the similar discussion above, we find the rational choice of institution i is equivalent to Eq. (3). Due to the fact that only the population in the fishing ground contribute to the fisheries profit of the institution i ($i = 1, 2$), therefore we can easily calculate the population abundance and the fisheries profit of institution i given rational choices of all institutions as

$$X_{n_a}^{m_0} = \frac{K}{n_a + 1}\left(1 + \alpha n_a + \sum_i^{n_a} b_i\right), \tag{20}$$

$$\pi_i^{m_0} = \frac{p_i r K}{(n_a + 1)^2}\left\{1 - \alpha - \left(n_a b_i - \sum_{j \neq i}^{n_a} b_j\right)\right\}^2, \tag{21}$$

where, superscript m_0 represents the quantity obtained when the exchange rate $m = 0$. Denoting $\bar{\rho}^{\cdot}$ as quantities obtained when $m = 0$, the proportion of the population abundance (Eq. (8) in the main text) becomes

$$\bar{\rho}^{\mathrm{pa}_{n_a}} = \frac{2}{n_a + 1}\left(\frac{1 + \alpha n_a + \sum_{j \neq i}^{n_a} b_j}{1 + \alpha + b_s}\right). \tag{22}$$

Also, one can easily see that $\bar{\rho}^{\mathrm{fp}_{n_a}}$ is equivalent to Eq. (8). Therefore, the statement P1 of Proposition A1 holds.

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Appendix B Effect of density-dependence in migration term

Here, we consider the effect of the density-dependent migration to see how the biological assumption alters our result obtained in the main text. One of the possible generalizations of the Eq. (4) to take density-dependent into consideration may be [1, 2]

$$M(x_1, x_2) = m\left\{\left(\frac{x_2}{K_2}\right)^{\beta}(1-\alpha)x_2 + \left(\frac{x_1}{K_1}\right)^{\beta}\alpha x_1\right\}, \tag{B.1}$$

where $K_1 = (1-\alpha)K$ and $K_2 = \alpha K$, and $\beta \geq 0$ determines the strength of density dependence. Larger value in β gives more intense density-dependence. Eq. (B.1) is equivalent to Eq. (4) when $\beta = 0$.

Figs. B.1 and B.2 is the effect of density-dependent migration with strength $\beta = 1$ (weaker density dependence) and $\beta = 2$ (stronger density dependence) on Eqs. (6) and (8). Both figures show the qualitatively similar effect especially when the cost of the fishing effort, c, is large. However, when the cost of the fishing effort c is small, the effect of density dependent migration becomes more prominent: intensive competitions between the institutions are observed in a wider range of parameter set (darker color).

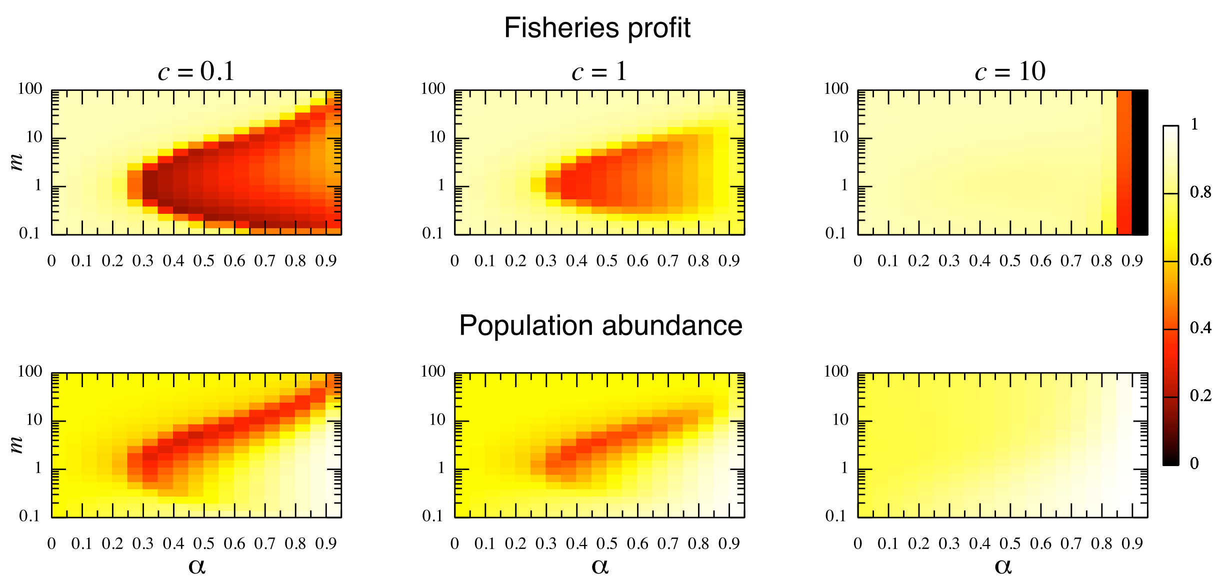

Figure B.1: Non-cooperative management with MPAs with a weaker density-dependent migration ($\beta = 1$). x axis is the fraction of MPAs, and y axis is the exchange rate between the patches, m. Each column has different values of the cost of fishing effort ($c = 0.1, 1, 10$). The first row shows the fractional decline of the gross fisheries profit ρ^{fp_2} relative to the sole-owner management (Eq. 6 in the main text). The second row shows the proportion of the total population abundance, $X^{\mathrm{Nash}_2}/X^{\mathrm{Sole}}$ (Eq. 8 in the main text), resulted in the non-cooperative management and the sole-owner management. Other parameter values are $r = 1$, $K = 100$. Note when the fraction of MPAs, α, is 0, it corresponds to the (non-spatial) Schaefer model.

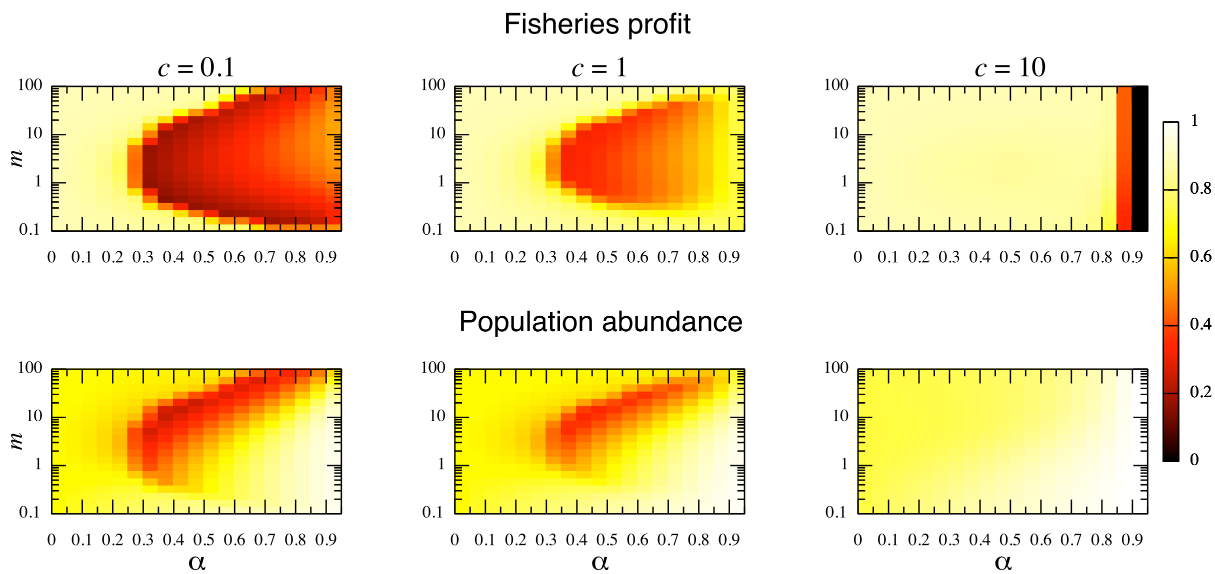

Figure B.2: Non-cooperative management with MPAs with a stronger density-dependent migration ($\beta = 2$). Other notations are the same as Fig. B.1.

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Appendix C Sensitivity analysis

Here we examine the sensitivity of the parameters dependence of the growth rate, r, carrying capacity, K, and relative difference in the efficiency parameter, b_i, to see how changes in the parameter values alter the results shown in the main text. Overall, our main conclusion are observed in many parameter sets That is, a prominent increase of competition occurs when exchange rate of the species between fishing ground and MPAs is not large, and intermediate fractions of the MPAs, although the range in the parameter space can shift slightly (Fig. C.1).

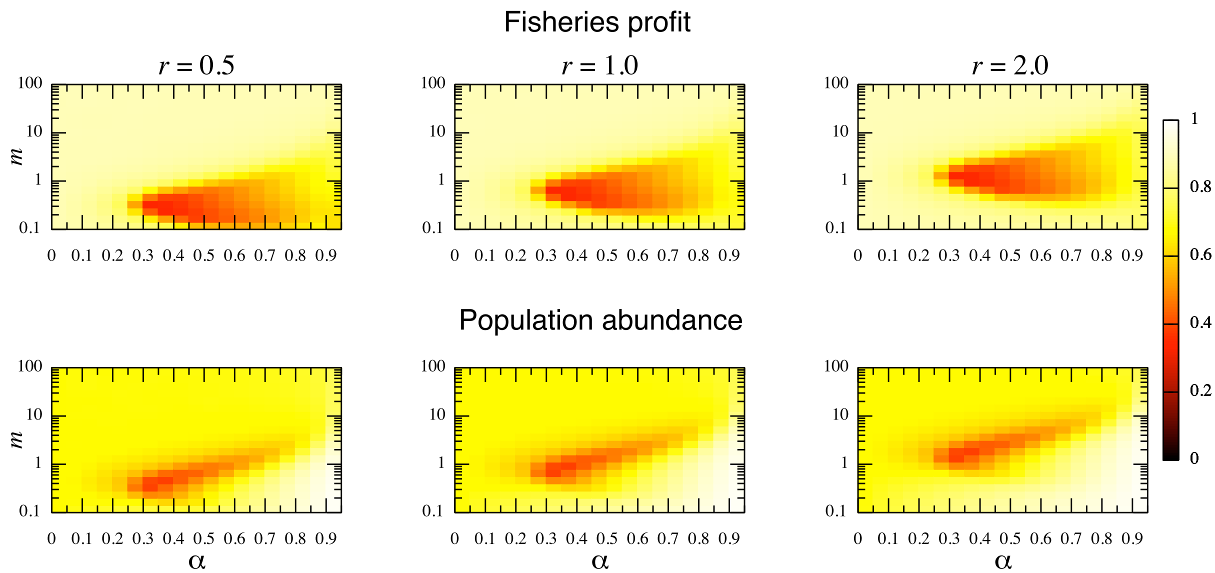

Figure C.1: Effect of different values of the growth rate $r = \{0.5, 1, 2\}$ on the non-cooperative management with MPAs. x axis is the fraction of MPAs, and y axis is the exchange rate between the patches, m. The first row shows the fractional decline of the gross fisheries profit ρ^{fp_2} relative to the sole-owner management (Eq. 6 in the main text). The second row shows the proportion of the total population abundance, $X^{\mathrm{Nash}_2}/X^{\mathrm{Sole}}$ (Eq. 8 in the main text), resulted in the non-cooperative management and the sole-owner management. Other parameter values are $c = 1$, $K = 100$. Note when the fraction of MPAs, α, is 0, it corresponds to the (non-spatial) Schaefer model.

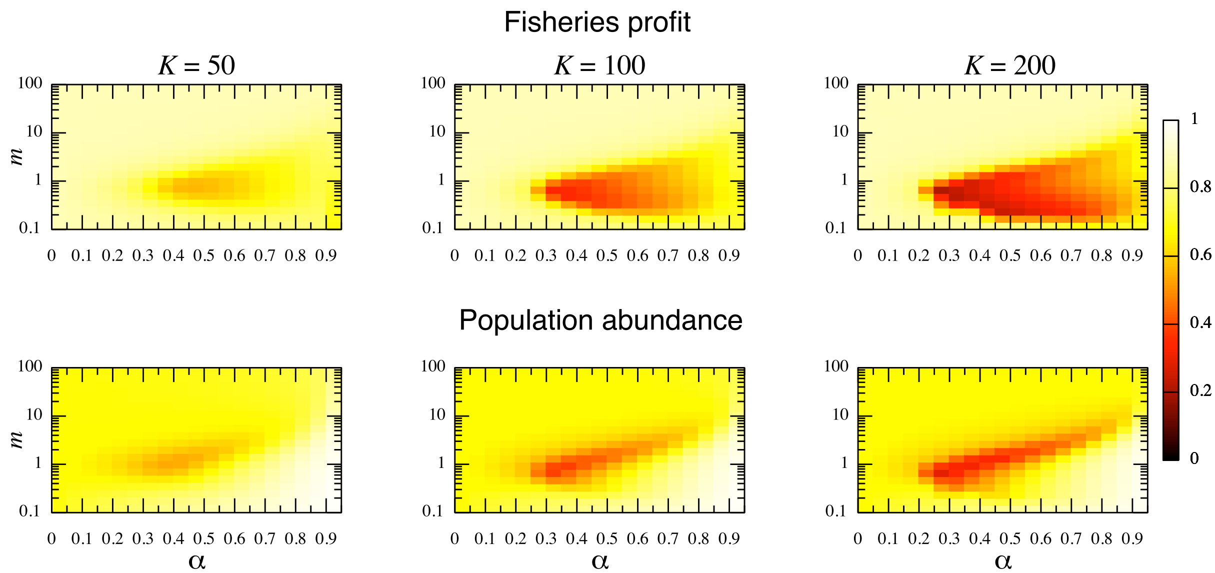

Figure C.2: Effect of different values of the carrying capacity $K = \{50, 100, 200\}$ on the non-cooperative management with MPAs. Other parameter values are $c = 1$, $r = 1$. Other notations are the same as Fig. C.1

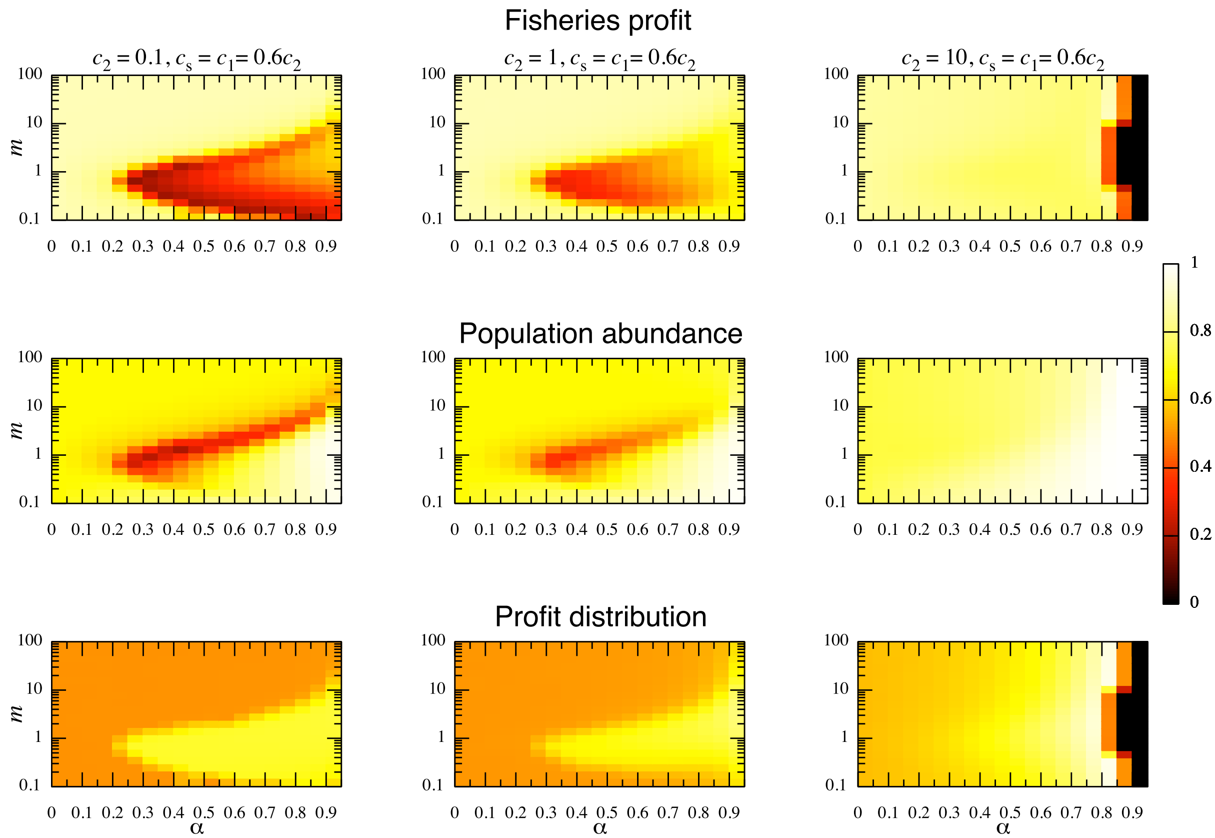

Figure C.3: Non-cooperative management with MPAs with different efficiency parameter ($b_2 = 0.6b_1 = 0.6b_s$). The third raw represents evenness of the distribution of the gross fisheries profit between institutions (Eq. 7 in the main text). $r = 1$, $K = 100$. Other notations are the same as Fig. C.1.